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Article

Evaluation of Interconnection Configuration Schemes for PV Modules with Switched-Inductor Converters under Partial Shading Conditions

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Abstract: Partial shading on photovoltaic (PV) arrays reduces the overall output power and causes multiple maximas on the output power characteristics. Due to the introduction of multiple maximas, mismatch power losses become apparent among multiple PV modules. These mismatch power losses are not only a function of shading characteristics, but also depend on the placement and interconnection patterns of the shaded modules within the array. This research work is aimed to assess the performance of 4×4 PV array under different shading conditions. The desired objective is to attain the maximum output power from PV modules at different possible shading patterns by using power electronic-based differential power processing (DPP) techniques. Various PV array interconnection configurations, including the series-parallel (SP), total-cross-tied (TCT), bridge-linked (BL), and center-cross-tied (CCT) are considered under the designed shading patterns. A comparative performance analysis is carried out by analyzing the output power from the DPP-based architecture and the traditional Schottky diode-based architecture. Simulation results show the gain in the output power by using the DPP-based architecture in comparison to the traditional bypassing diode method.

Keywords: partial shading; photovoltaic (PV) arrays; multiple maximas; mismatch; differential power processing (DPP); series-parallel (SP); total-cross-tied (TCT); bridge-linked (BL); center-cross-tied (CCT)

1. Introduction

Solar energy is free and abundant [1]. Environmental concerns are widely reduced by using solar energy for power generation. Therefore, the photovoltaic (PV) energy is becoming the most emerging and promising solution to address environmental problems. Generally, the efficiency of solar PV energy conversion using PV panels is low [2], and therefore, many researchers are working on improving the efficiency and output energy yield [3]. Factors that may affect the conversion efficiency generally include the effect of soiling, dirt and dust, elevated temperature, and sudden irradiance changes [4]. Similarly, the output power produced by PV arrays is remarkably reduced due to partial shading conditions [5,6]. Partial shading is generally induced over a PV module, string, or on a whole small PV system. It is due to cloud shadows, dust, permanent cracks on shields or surfaces; as well as shade due to various structures including trees, leaves, and buildings or towers [7]. Partial shading causes a reduction in the irradiance, and also distributes irradiance in a non-uniform pattern over the surface of various PV modules in an array [8,9]. Hence, the current from the PV array is constrained by the shaded PV modules, which in turn is detrimental for the other healthy PV modules connected in the series [10]. Consequently, in practice, a parallel-connected diode termed as a bypass diode (D_1 and D_2) is installed across it to minimize the effects of mismatching, as shown in Figure 1a. During mismatching, this bypass diode will be ON and the current starts flowing through it (as shown in

Figure 1b). In this case, various maximas appear on the power–voltage (P–V) characteristics. These multiple peaks are known as local maxima's, as exemplified in Figure 1c. When multiple peaks are present, the conventional maximum power point techniques (MPPTs) may not work accurately. Therefore, a global maximum power point technique (GMPTT), capable to distinguish between local and global maxima is generally needed to maximize the overall output power from the array. In the literature, many conventional MPPT techniques have been presented and their behavior on partial shading conditions is analyzed [11–13]. Various artificial intelligence techniques including fuzzy logic [14,15], neural networks [16], and genetic algorithms [17] are generally employed to track the global maximum power point (GMPP). However, these techniques have limitations and exhibit false tracking over varying conditions of irradiance and temperature. Furthermore, the conventional MPPT methods should be retrofitted with more sensing and control requirements [18,19].

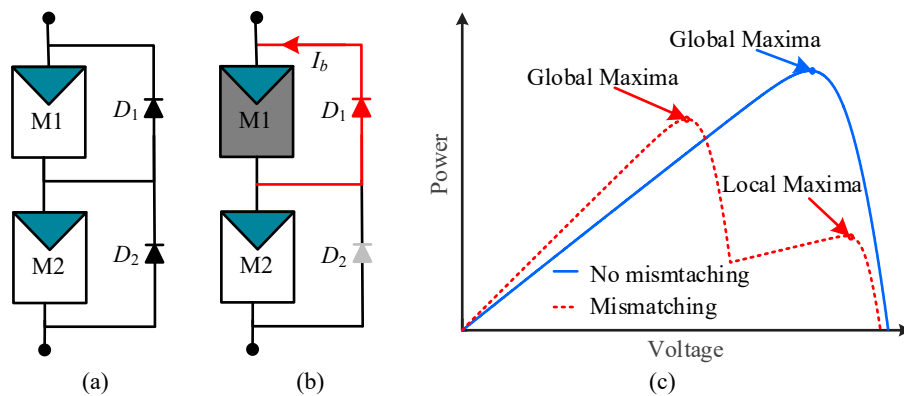


Figure 1. A PV module (M1 and M2) with parallel-connected bypass diodes D_1 and D_2 : (a) schematic diagram, (b) schematic showing the current flow direction while shaded and bypassed [19], (c) P–V characteristic of series-connected two PV modules while one is shaded (mismatching occurs). Here, I_b is a bypass current through D_1 .

In addition to developing advanced MPPT algorithms, an alternative is to directly mitigate the local peaks under partial shading. Differential power processing (DPP) converters [20–25] are typical representatives, that enable each PV module to produce maximum output power. DPP converters eliminate the problem of multiple maximas in the PV string, as highlighted in Figure 2. In addition, Figure 3a further exemplifies one DPP configuration known as the PV–PV voltage balance converter [20]. This PV–PV converter only processes the mismatched power and thus, it is used in this paper. The working principle of the PV–PV DPP is shown in Figure 3b,c, where the PV module M1 is shaded and the PV module M2 in the non-shaded mode. I_L is a mismatch current, which passes through the inductor L . The transistors Q_1 and Q_2 operate complementarily to each other. Nevertheless, the switching will induce power losses that can be found as [20]

$$P_{SWLOSS} = 2k_0 \left[V_G \sqrt{\frac{V_G}{2V_B}} + 4V_D I_L \sqrt{\frac{V_D}{V_B}} \right] f_{sw} \quad (1)$$

in which k_0 is a material property dependant device constant, V_B is the breakdown voltage of the device, V_D is the voltage at the device terminal, V_G is the voltage at the gate terminal, I_L is the current passing through the inductor, and f_{sw} is the switching frequency of the power device. The PV–PV DPP topology is based on the switched-inductor between two PV modules. Therefore, it is named as switched-inductor (SL)-based topology. The SL-based topology can be represented by a simplified model as illustrated in Figure 4. To have the same voltage (i.e., V_1 and V_2) across both PV modules, the value of effective impedance Z_{EFF} should be minimum. However, practically it is unavoidable to have zero value of Z_{EFF} but since the value of Z_{EFF} is frequency dependent. Therefore, it is possible to achieve the minimum value by operating the converter at frequencies near to the resonant frequency.

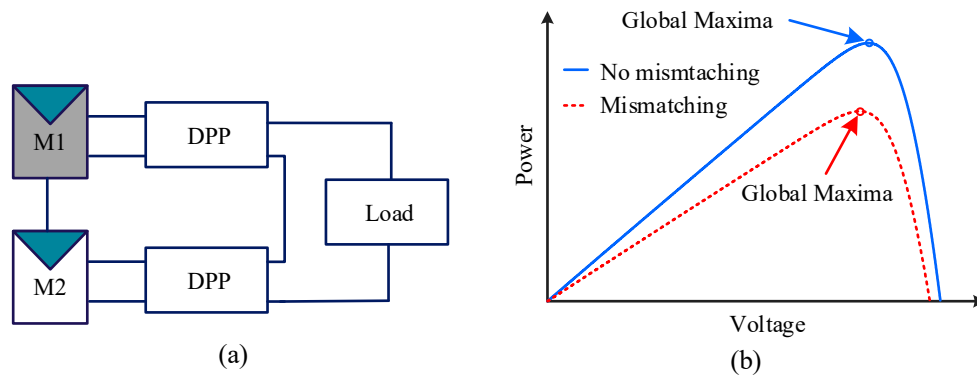


Figure 2. PV modules (M1 and M2) with parallel-connected DPP topologies: (a) schematic diagram when M1 is shaded and (b) P–V characteristic of series-connected two PV modules during mismatching and no mismatching.

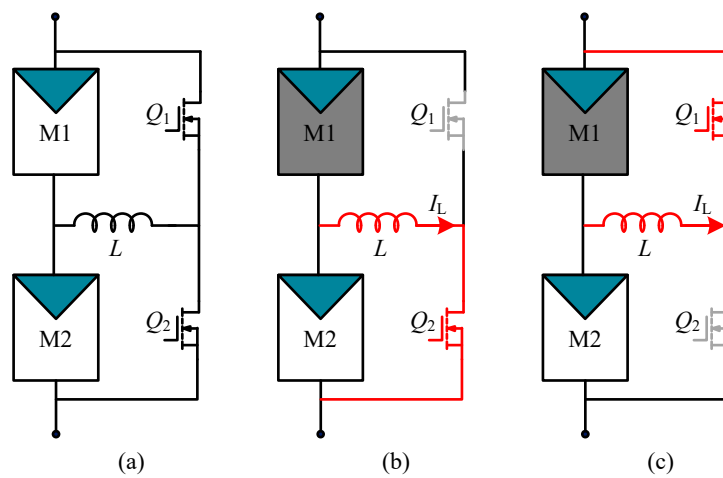


Figure 3. Switched-inductor (SL)-based PV–PV voltage balance converter [20]: (a) schematic diagram containing two series-connected PV modules M1 and M2 without shading; (b) M1 is shaded, where Q_1 is ON and Q_2 is OFF; and (c) M1 is shaded and Q_1 is OFF and Q_2 is ON. Here, I_L is a current passing through an inductor L .

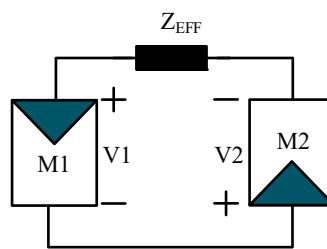


Figure 4. Equivalent circuit for the SL-based DPP technique. Here, Z_{EFF} is the effective impedance, V_1 , and V_2 are the voltages across the PV module M1 and M2, respectively.

Moreover, another important factor to consider in the design of the SL-based topology is the quality factor Q , which is given by expression (2)

$$Q = (1/R_{ESR}) \sqrt{L/C} \quad (2)$$

where L is the inductance shown in Figure 3 and C is the stray capacitance, which can be neglected as its value is very small. For practical reasons and to have adequate voltage stress across inductor L , the value of Q is selected in the range of 1–10 and the switching frequency is selected as 50 kHz.

The value of switching frequency is selected closer to the resonant frequency in order to have a minimum value of Z_{EFF} . For better understanding, Z_{EFF} can be considered as a series LC network whose impedance versus frequency curve is shown in Figure 5, which can be calculated by using (3). At lower frequencies (below resonant frequency), the topology behaves as overall capacitive. However, as the frequency increases, the value of Z_{EFF} decreases to its minimum value at the resonant frequency where the impedances of L and C cancels each other. Similarly, beyond the resonant frequency and at higher frequencies, the nature of Z_{EFF} is overall inductive. Therefore, the value of switching frequency is selected in the vicinity of resonant frequency to achieve a minimum value of Z_{EFF} , which will, in turn, equalizes the voltages of PV modules in a system. Moreover, the value of switching frequency is selected to be higher than the resonant frequency to achieve soft-switching operation for all the switches, which can minimize the switching power loss.

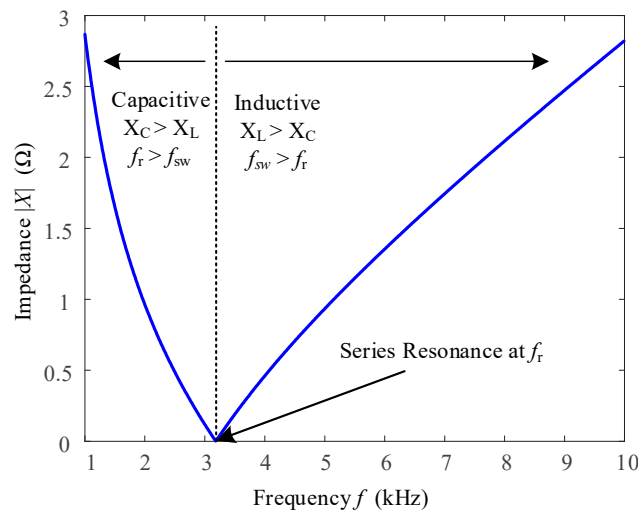


Figure 5. A curve showing the variation of impedance with frequency for a series resonant circuit.

$$|X| = |X_L| - |X_C| \quad (3)$$

where X_L is the inductive impedance and X_C is the capacitive impedance.

The power losses during partial shading are dependent upon the patterns of shading. Various schemes have been presented in the literature to minimize the detrimental effects caused by non-uniform shading [26]. One possibility is to reconfigure the interconnection PV modules in case if there is partial shading. The most commonly used interconnection scheme for PV arrays is series-parallel (SP). Configurations like the bridge-linked (BL), central-cross-tied (CCT), and total-cross-tied (TCT) (see Figure 6) can also be adopted to minimize the mismatching effect due to partial shading [27]. Although, it has been revealed that the TCT configuration yields maximum power for conventional bypass technique [28], more attempts have been made to mitigate the effects of partial shading using SP configurations due to its simplicity [29]. Using TCT enhances the longevity of the PV module with an estimated increase in a lifetime by 30% [30]. Alternately an electronic array reconfiguration scheme abbreviated as EAR has been proposed, which may modify the interconnection pattern of modules using electronic switches. In EAR, during operation and the decision of reconfiguration is based upon the pattern of shading, while control is achieved using a switch matrix [31]. The electrical reconfiguration using switches and relays, which can be effectively realized for small systems. However, for large PV arrays in solar parks, etc., the electronic switches, their interaction, and controllability becomes complex and difficult to handle due to the constraints of switching [32]. Similarly, another technique termed as disperse interconnection scheme (SDS) for multiple PV modules in an array has been presented in [33]. This technique is also based on changing the electrical configuration of the modules in the PV array. This technique has superior output yield in comparison to other

interconnection schemes as discussed in [29]. However, cost and complexity associated with the changing connections in large PV arrays can be cumbersome, and the overall system yield may become infeasible [29]. Therefore, various aspects by including efficiency and cost must be carefully considered for the optimal system design. A static reconfiguration is considered effective over other dynamic interconnection techniques [23]. The static reconfiguration technique does not involve the dynamic change of interconnection. It is based upon the one-time constant arrangement of PV modules with predefined interconnection settings in an array under different partial shading conditions [34,35]. Different interconnection topologies, which are discussed above—namely, SP, BL, and TCT for PV arrays—have been proposed. These interconnection schemes are tested by using intelligent power electronics to minimize power losses due to mismatch. The power electronic-based technique replaces the shunting bypass diodes, which are generally connected in parallel to PV modules in the array.

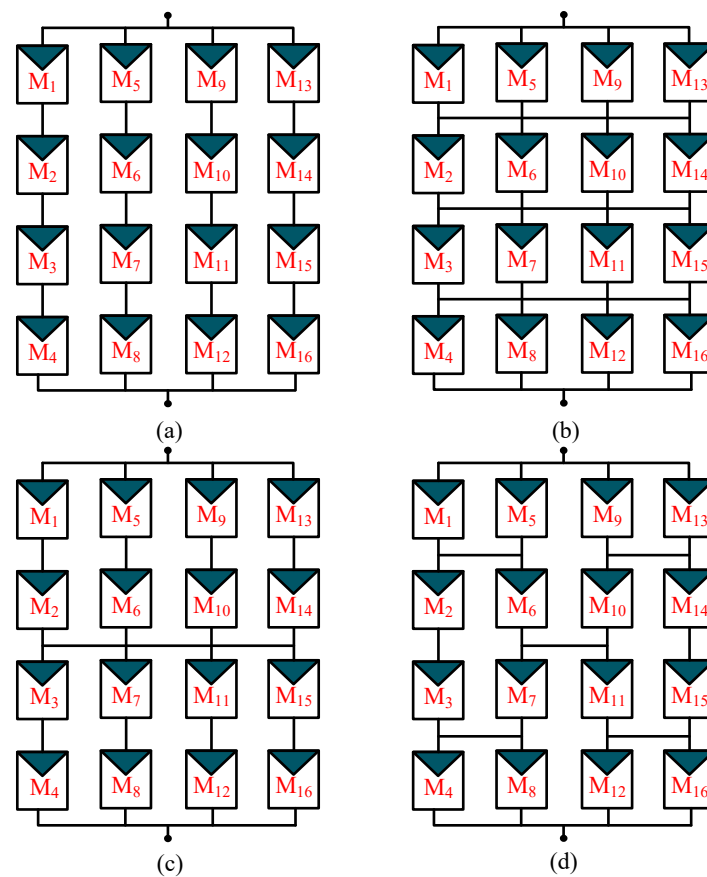


Figure 6. PV array topologies: (a) series-parallel (SP), (b) total-cross-tied (TCT), (c) central-cross-tied (CCT), and (d) bridge-linked (BL).

The performance analysis of above-mentioned interconnection schemes has been widely discussed with traditional bypass diodes in the literature so far. However, when DPP converters have adopted the performance of those configurations has not yet been explored. Therefore, in this paper, the four array interconnection schemes—i.e., the SP, TCT, CCT, and BL configurations with SL-DPP—are tested under different patterns of shading and irradiance. The performance of proposed schemes (SL-based interconnection schemes) is evaluated by introducing different shading patterns and its comparison with state of the art topology, i.e., bypass diode (for comparative analysis). This study uses a 4×4 PV array of system, which has a size of 968 W. The output power and mismatch losses under various shading patterns with SL-DPP and bypass diodes are presented. The organization of the rest of the paper is given below. Section 2 introduces the different interconnection configurations and shading

pattern designs. Section 3 outlines various important results and based upon the highlighted results conclusions are outlined in Section 4.

2. Configurations and Shading Pattern Designs

The four interconnection schemes—i.e., the SP, TCT, CCT, and BL configurations—are compared at different shading patterns for the 4×4 PV array. The PV array with these configurations using DPP converters and bypass diodes are evaluated. The rating of PV modules is given in Table 1. The rated maximum output power from the 4×4 PV system is 968 Watt at 1000 W/m^2 and STP. Different types of shading patterns including, one module shading, short wide, long narrow shading, central shading, and diagonal shading are applied at all above discussed interconnection schemes on 4×4 PV array at different irradiances, as shown in Figure 7. The variations in irradiance from 200 W/m^2 to 800 W/m^2 with a difference of 100 W/m^2 is considered to compare the performance of SL-based DPPs with conventional parallel-connected bypass diodes. Various shading pattern designs for PV array configuration schemes are as follows.

Table 1. Specification of the PV module at STC (1000 W/m^2 and 25°C).

Parameters	Rating
Rated Peak Power (P_{\max})	60 W
Voltage at MPP (V_{mp})	17.10 V
Current at MPP (I_{mp})	3.50 A
Open Circuit Voltage (V_{oc})	21.10 V
Short Circuit Current (I_{sc})	3.80 A

2.1. One Module Shading

In the condition of one module shading, one module from first row and first column is shaded from 4×4 PV array, i.e., PV module M1, as shown in Figure 7a.

2.2. Short Wide Shading

For short wide shading, four PV modules from the first two rows and columns are shaded, i.e., M1, M2, M5, and M6, as shown in Figure 7b.

2.3. Long Narrow Shading

In long narrow shading, PV modules placed at the last column of PV array, which includes PV modules, M13, M14, M15, and M16 along with the last row, which are M4, M8, and M12 are not shaded, as shown in Figure 7c. Rest of all PV modules are shaded from 4×4 PV array.

2.4. Central Shading

Four PV modules from the center are shaded—i.e., M6, M7, M10, and M11—while all other remain unshaded, as shown in Figure 7d.

2.5. Diagonal Shading

For diagonal shading M4, M7, M10, and M13 are shaded, as shown in Figure 7e. In diagonal shading, one module gets shaded from each row and column of a 4×4 PV array for all configuration schemes.

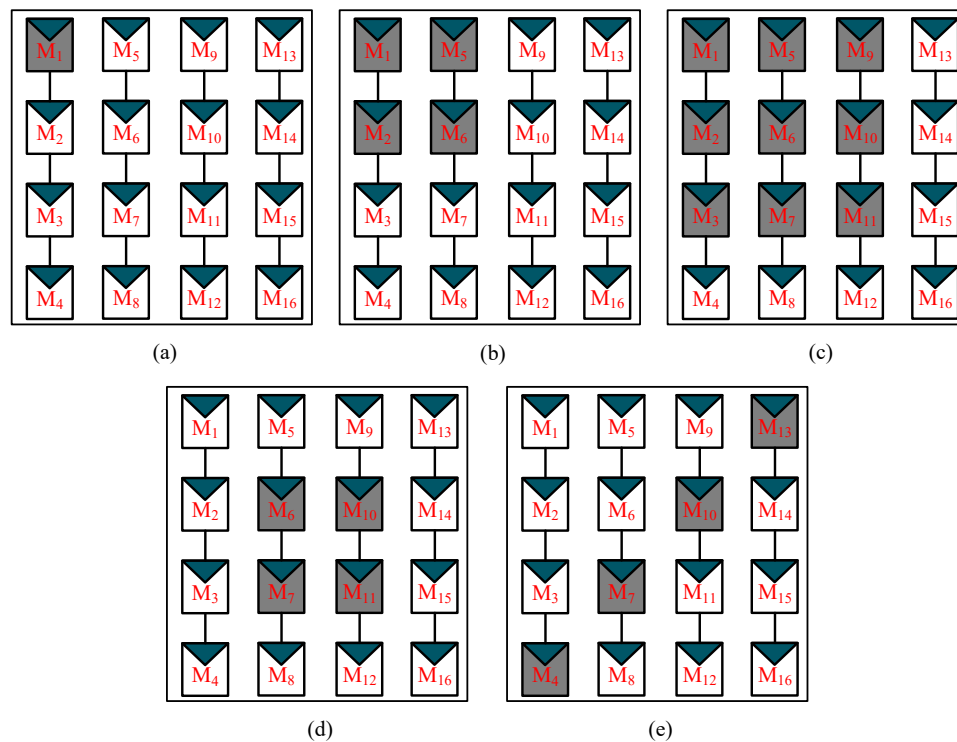


Figure 7. Shading pattern designs for PV array configuration schemes: (a) one module, (b) short wide, (c) long narrow, (d) central, and (e) diagonal.

3. Results and Discussion

The simulation results for the configurations with traditional bypass diodes and power electronic-based DPP architectures are shown in Figures 8–11. The systems are evaluated at 1000 W/m², 800 W/m², 600 W/m², 500 W/m², 400 W/m², and 200 W/m² by using a power sim (PSIM).

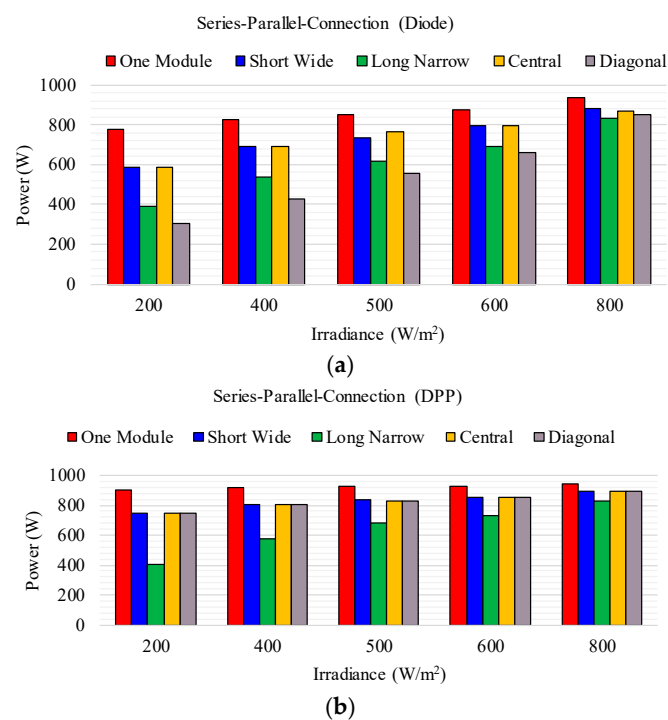


Figure 8. Output for series-parallel (SP) connection under various shading conditions with: (a) diode connection and (b) DPP connection.

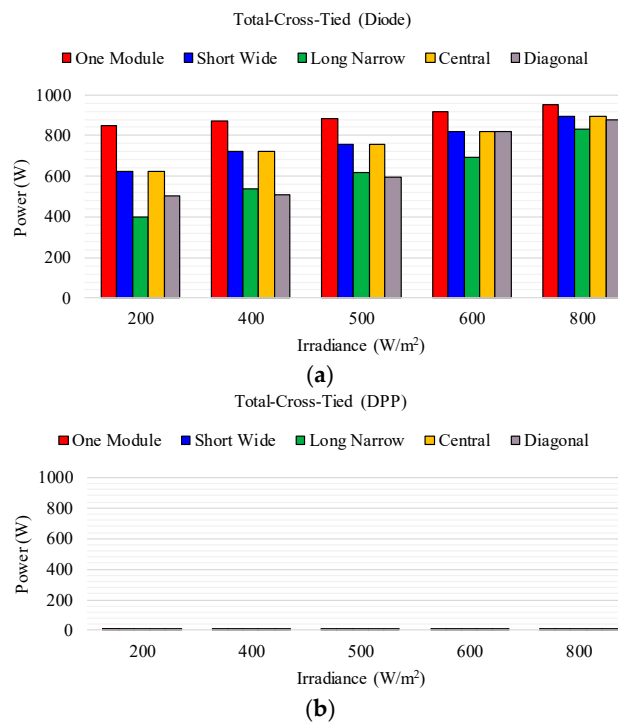


Figure 9. Output for total-cross-tied (TCT) connection under various shading conditions with: (a) diode connection and (b) DPP connection (zero output).

The unshaded modules in Figure 7 experience an irradiance of 1000 W/m^2 . It is seen in Figures 8 and 10 that PV strings with DPP architectures have higher output power for the SP and CCT configurations than the systems with traditional bypass diodes. However, when DPP converters are adopted, there is almost zero or below 1 W of output power for all the shading scenarios with the TCT and BL configurations, as shown in Figures 9b and 11b. As the SL-based DPP architecture requires at least two series-connected PV modules for the converter to work properly, as shown in Figure 3. However, in TCT and BL architectures, their interconnections with other parallel PV strings affect the working principle of the used SL-based DPP topology.

In SP configuration, the output power for bypass diode and DPP under all shading patterns is shown in Figure 8a,b. The output power is 778 W, 826 W, 847 W, 872 W, and 933 W with bypass diode for one module, short wide, long narrow, central, and diagonal shading patterns, respectively, as shown in Figure 8a. In SP, output power with proposed SL-based DPP architecture is 905 W, 918 W, 924 W, 930 W, and 942 W at 200 W/m^2 , 400 W/m^2 , 500 W/m^2 , 600 W/m^2 , and 800 W/m^2 , respectively during one module, short wide, long narrow, central, and diagonal shading, respectively (see Figure 8b). For bypass diode technique, the power output in SP using short wide and central shading is almost similar as four PV modules are shaded under both schemes, two from each PV strings. Whereas, in the diagonal shading, each module is shaded from each parallel-connected PV string. Therefore, it has a more severe effect on output power, especially for diode bypass architecture, which can be seen from Figure 8a. DPP with SP interconnection, which is shown in Figure 8b has almost the same output power under given irradiances.

The power output received from CCT interconnection is shown in Figure 10. Similar to SP, in CCT one module shading has maximum power for all shading patterns, i.e., 821 W, 857 W, 870 W, 900 W, and 945 W at 200 W/m^2 , 400 W/m^2 , 500 W/m^2 , 600 W/m^2 , and 800 W/m^2 , respectively with bypass diode architecture. Similarly, 905 W, 918 W, 925 W, 930 W, and 942 for SL-based DPP architecture at 200 W/m^2 , 400 W/m^2 , 500 W/m^2 , 600 W/m^2 , and 800 W/m^2 , respectively under one module shading scheme.

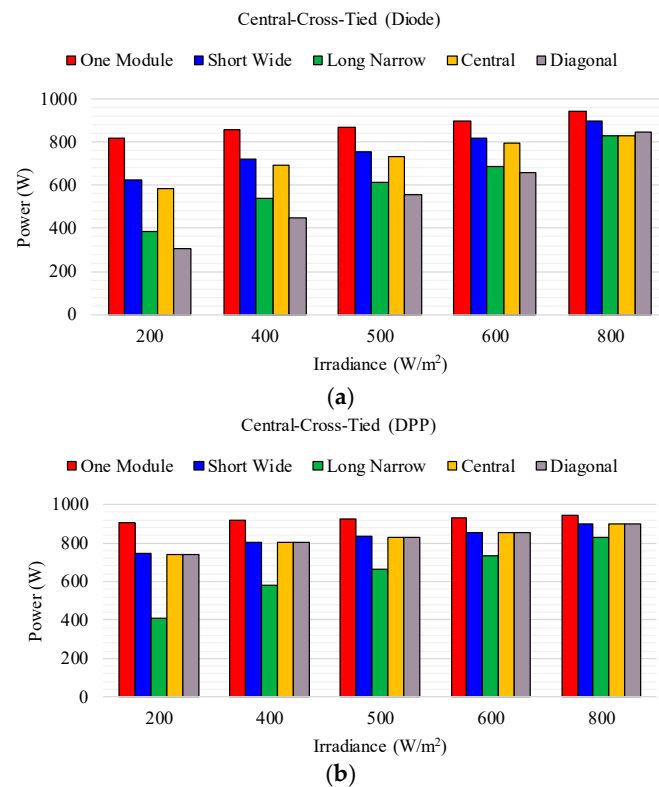


Figure 10. Output for central-cross-tied (CCT) connection under various shading conditions with: (a) diode connection and (b) DPP connection.

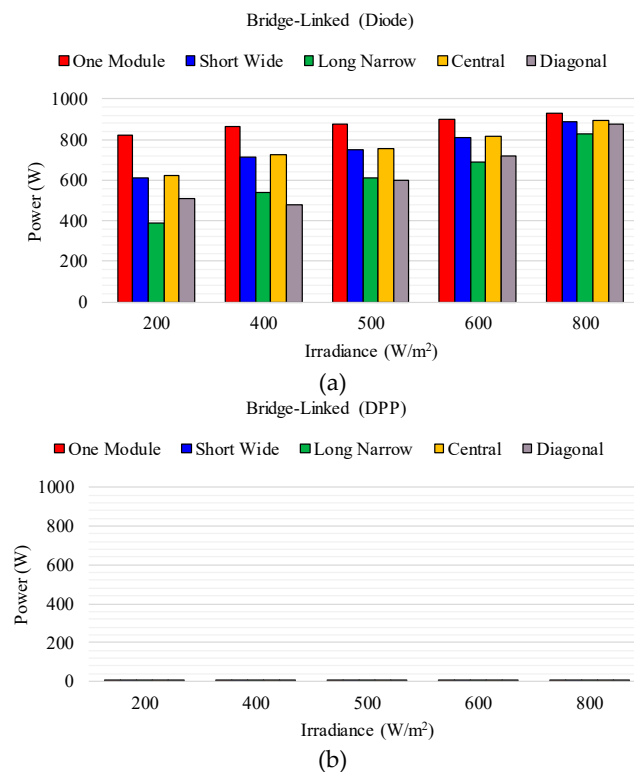


Figure 11. Output for bridge-linked (BL) connection under various shading conditions with: (a) diode connection and (b) DPP connection (zero output).

For short wide, long narrow, central, and diagonal shading the output power is given in Figure 10a,b with bypass diode and DPP, respectively. Figures 9 and 11 show the output power from TCT and

BL interconnections for the traditional diode. In TCT and BL connections, DPP architecture is not applicable as discussed before. Therefore, the output power is almost 0 W, as shown in Figures 9b and 11b. Power losses are also calculated from Figures 8 and 10 during one module, short wide, long narrow, central, and diagonal shading for SP and CCT traditional bypass diodes and DPP converters. These losses are calculated only for the SP and CCT interconnections because TCT and BL interconnection schemes are not applicable on the SL-based DPP converter. For instance, power losses during one module shading for the worst case—i.e., 200 W/m² are 15.34%, 10.66% for SP and CCT, respectively by using the bypass diode. It is only 1.52% for the DPP architecture by using SP and CCT interconnections during one module shading. The power losses decrease with an increase in irradiance. For short wide and long narrow shading at 200 W/m², the power losses for traditional bypass diode are 24.19% and 19.12% during short wide and 40.42% and 40.73% during long narrow shading for SP and CCT, respectively. Similarly, at 200 W/m², DPP architecture has 3.66% and 3.40% power losses during short wide shading for SP and CCT, respectively. Power loss for DPP during long wide shading is 37.51% and 40.58% for SP and CCT at 200 W/m². For the rest of the irradiances, the power loss decreases as the irradiance increases both for diode and DPP.

The power losses for SP and CCT string interconnections during central and diagonal shading for diode at 200 W/m² is 24.19% both for SP and CCT while 4.11% by using DPP. During diagonal shading, it has similar power losses for SP and CCT interconnections, which is 60.85% for bypass diode and 4.05% for DPP at 200 W/m². Similarly, these power losses decrease with an increase of irradiance in a diagonal shading pattern also. Overall, PV strings with SP and CCT interconnections with DPP architecture have more output power than a traditional diode. For short wide, central, and diagonal shading, PV strings with DPP architecture are producing almost the same output power because four PV modules are shaded for all of them. DPP architecture is not applicable to TCT and BL interconnections. In all, DPP extracts more power from the 4 × 4 PV array system than traditional bypass diode for all interconnection schemes where it is applicable. However, SL-based DPP topology has higher cost with a complex circuitry in comparison to traditional bypass diode topology.

4. Conclusions

In this paper, a DPP converter has been used in PV modules with different static interconnection schemes including series-parallel (SP), total-cross-tied (TCT), central-cross-tied (CCT), and bridge-linked (BL). The power production from the PV modules under various interconnection schemes and mismatch conditions have been explored. More importantly, a comparison of the power production between the traditional bypass diode and the DPP-based architecture for a 4 × 4 PV array has been performed. It has been found that the two configurations—i.e., SP and CCT with the DPP converters—produce more power than traditional bypass diode-based architecture. On the other hand, TCT and BL configurations are not suitable for integrating the DPP converters due to their inherent hardware limitations. Hence, the DPP-based interconnection might be a promising solution to enhance the energy yield for PV modules with minimal mismatch power losses during partial shading conditions. It is especially suitable for the SP configuration, which is the most commonly used configuration in practice. However, the integration of DPP converters will inevitably increase the cost and complexity of the overall system, which requires further analysis.

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